2-bit Optical Decoder based on 4×4 Multi-mode Interferometer Coupler for BPSK-modulated signals

Yohei Aikawa  
Laboratory for Future Interdisciplinary Research of Science and Technology, Institute of Innovative Research, Tokyo Institute of Technology  
Kanagawa, Japan  
aikawa.y.aa@m.titech.ac.jp

Hiroyuki Uenohara  
Laboratory for Future Interdisciplinary Research of Science and Technology, Institute of Innovative Research, Tokyo Institute of Technology  
Kanagawa, Japan  
uenohara.h.aa@m.titech.ac.jp

Abstract—A compact 2-bit optical decoder consisting of a 4×4 multi-mode interferometer coupler with silicon waveguide is presented. The numerical results show that the device activates one of four outputs ports depending on the bit combinations of two BPSK signals.

Index Terms—optical decoder, multi-mode interferometer

I. INTRODUCTION

With the dramatic increase in data traffic of digital infrastructure, the performance of Complementary Metal Oxide Semiconductor (CMOS) computers must be continuously improved, as expressed by Moore’s Law. However, the computation latency is already saturated due to the increase of resistance-capacitance (RC) delay caused by CMOS miniaturization. It has been suggested that this limitation could be circumvented by introducing optics into computers, since light propagation is not affected by RC delays. Optical computing is expected to be a promising solution that significantly reduces computational latency.

There have been several types of studies on optical computing. AND gates [1], [2], OR gates [3], half adders [4], [5], and decoders [6], [7]. In particular, it is remarkable in that decoder is a functional elements with excellent versatility that can be applied to instruction decoding in a processor. Teimoori et al. [6] and Cabezon et al. [7] have demonstrated optical decoders by using semiconductor optical amplifiers. However, both schemes rely on optical nonlinearity, which prevents them from reducing the device length, and computational latency remains limited.

In recent years, some experimental demonstrations of optical logic gate employing linear optical effects have been proposed [8]–[11]. These schemes have the advantage of miniaturization because they do not depend on nonlinear optical effects. Although basic logic gates have already been implemented, more complex combinational logic circuits have not been realized.

In this paper, we newly propose an optical decoder. The novel device is provided by the form of a 4×4 multi-mode interferometer (MMI) coupler. Since this device does not use nonlinear optical effects, it is compact and has a small latency.

II. PRINCIPLES

Figure 1 shows the configuration of the optical decoder. This device consists of a 4×4 MMI coupler, and it operates as a decoder for 2-bit binary phase-shift keying (BPSK) signals. This is a 2-to-4 line decoder that activates one of four output ports depending on each 2-bit input value. However, unlike electronic decoders, it requires a probe light input in addition to the 2-bit signal.

First, the light power at the output of the MMI is derived by defining the two BPSK signals A and B and a probe light in the following form:

\[
E_A = \sqrt{P_S} \cdot e^{i\omega_S t + \theta_A}, \quad E_B = \sqrt{P_S} \cdot e^{i\omega_S t + \theta_B}, \quad E_P = \sqrt{2P_P} \cdot e^{i\omega_P t + \theta_P},
\]

where, \(P_S, P_P, \omega_S, \) and \(\omega_P\) represent the light power and the angular frequencies of the signal and the probe, and \(\theta_A, \theta_B,\) and \(\theta_P\) are the phases of the signal A, signal B, and the probe, respectively. In this paper, it is assumed that both frequencies of the signal and the probe are the same \((\omega_S = \omega_P)\). According to self-imaging principle [12], the phases \(\phi_{ij}\) in a 4×4 MMI coupler associated with imaging from an input port \(I_i\) to an output port \(O_j\) are given by

\[
\begin{pmatrix}
O_1 \\
O_2 \\
O_3 \\
O_4
\end{pmatrix}
= \frac{1}{2}
\begin{pmatrix}
1 & e^{i\Delta \phi} & e^{-i\Delta \phi} & 1 \\
e^{i\Delta \phi} & 1 & 1 & e^{-i\Delta \phi} \\
e^{-i\Delta \phi} & 1 & 1 & e^{i\Delta \phi} \\
e^{i\Delta \phi} & 1 & 1 & e^{-i\Delta \phi}
\end{pmatrix}
\begin{pmatrix}
I_1 \\
I_2 \\
I_3 \\
I_4
\end{pmatrix},
\]
Here, two light signals $E_A$ and $E_B$ are input to the ports of $I_2$ and $I_3$, and the probe $E_P$ is input to the port of $I_4$. The signal waves and the probe wave combine in the MMI coupler and yield the output field. In Figs. 2 (a)-(d), the output powers $O_1O_1^* \sim O_4O_4^*$ as a function of the probe phase $\theta_P$ were derived for each condition where the two phases of the BPSK signals ($\theta_A$, $\theta_B$) are (0, 0), (0, $\pi$), $(\pi, 0)$, and $(\pi, \pi)$. When the probe phase $\theta_P$ is given by 0, the results show that each output is maximized at a different port depending on the 2-bit pattern of signals A and B. This is the decoder operation. In addition, the maximum and minimum powers in each case are 0.63 and 0.13, respectively; the power ratio is given by 5:1.

Figure 3 shows the operation examples with the signal constellations where the signal phases ($\theta_A$, $\theta_B$) are (0, 0), (0, $\pi$), $(\pi, 0)$, and $(\pi, \pi)$. In Fig. 3 (a), the signals A and B interfere constructively at the ports $O_2$ and $O_3$. In contrast, at the ports $O_1$ and $O_4$, both signals are in opposite phase relationship and cancel each other. Furthermore, the probe light interferes almost in-phase at port $O_2$, but out-of-phase at $O_3$. Therefore, only port $O_2$ has the maximum intensity. Consequently, the absolute value of electric field intensity at the port $O_2$ is $\sqrt{5}$ times higher than at the other ports, and the light intensities at all ports except $O_2$ are the same. Figure 3 (d) is almost the same situation, but the phase relationship of the signals is the opposite of the case in Fig. 3 (a), resulting in the maximum intensity at $O_3$. In the case of Figs. 3 (b) and (c), the interference result changes. According to Fig. 3 (b) and (c), either $O_1$ or $O_4$ port is maximized. Consequently, it is confirmed that the outputs from the different ports are maximized depending on the bit patterns same as Fig. 2.

III. SIMULATION RESULTS

The feasibility of the optical decoder is evaluated by numerical simulation. Figure 4 shows the simulation model of the optical decoder consisting of a 4 x 4 MMI coupler. The device is made of silicon and provided in the form of waveguide. The waveguide is centered within a silicon dioxide (SiO$_2$) cladding layer, and it has a 0.22 $\mu$m thickness. Figure 4(b) is a top view of the device. The entire of the MMI coupler is a simple rectangular body with a 2.64 $\mu$m width and a 11.4 $\mu$m length. The MMI length is determined by the MMI width to satisfy $L = 3L_c/4$; where $L_c$ is a beat length. The four input ports and the four output ports consist of tapered waveguides, and they are labeled as $I_1 \sim I_4$ and $O_1 \sim O_4$, respectively. The parameters required to design the MMI coupler are listed in Tab. I.

The numerical simulation for the optical decoder is implemented through the three dimension finite-difference time-domain method. The electrical field was numerically calculated when two BPSK signals are input to the ports $I_2$ and $I_3$, and a probe light is input to the port $I_4$. In the simulation, the probe phase $\theta_P$ was set to be zero. All optical signals were
set to be a wavelength of 1550 nm. The probe intensity was set to be $\sqrt{2}$ times larger than that of the signals A and B.

Figure 5 shows the distributions of absolute value of electric field $|E|$. Figures (a-d) and (a’-d’) are the distributions seen from the top of the MMI and from the cross section at output end, respectively. The four groups of the figures (a, a’), (b, b’), (c, c’), and (d, d’) correspond to the conditions when the phases of the signals $\theta_A, \theta_B$ are 0-0, 0-\pi, \pi-0, and \pi-\pi.

In addition, the power value $|E|^2$ in each port exactly matched the theoretical value.

### Conclusion

In this paper, a compact optical decoder based on linear optical effects is presented. The device is a 2-bit decoder that activates one of four outputs ports depending on the bit combinations of two BPSK signals. The decoder consists of a 4x4 MMI, and it requires a probe light in addition to the two BPSK signals for proper operation. The numerical results show that only one output is shown to be maximized at different ports when the bit combinations of two BPSK signals are (0, 0), (0, \pi), (\pi, 0), and (\pi, \pi). The power ratio at the maximum and minimum ports in each case are given by 5:1.

### Table I

<table>
<thead>
<tr>
<th>Parameter</th>
<th>T</th>
<th>W</th>
<th>$W_p$</th>
<th>L</th>
<th>$L_4$</th>
</tr>
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<tbody>
<tr>
<td>Value ($\mu m$)</td>
<td>0.22</td>
<td>2.64</td>
<td>0.44</td>
<td>11.4</td>
<td>2.0</td>
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</table>

Fig. 5. Electric field distributions $|E|$ of the optical decoder: (a-d) top of view and (a'-d') output side cross section of the 4x4 MMI. The four groups of the figures (a, a’), (b, b’), (c, c’), and (d, d’) correspond to the bit combinations of two BPSK signals A and B: (0, 0), (0, \pi), (\pi, 0), and (\pi, \pi).

### References


